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Phase retrieval in optical fiber modal interference for structural health monitoring

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ABSTRACT

A method based on data dependent system (DDS) for extraction of phase in fiber modal interference is presented. The interference patterns of LP_{01} & LP_{11}, LP_{01} & LP_{02} and LP_{06} &LP_{07} within the fiber have been recorded under different launching conditions. The patterns were characterized by means of autoregressive model and the self coherence functions of the corresponding interferogram were determined. It would provide the phase distribution of the pattern and the modulation of group delay due to the measurand. An application has been made for measuring strain in a simply supported beam under different loading conditions. Results are presented for the applied strain in the range of 270–1500 μ strain.

1. Introduction

In recent years, there is a growing demand for health monitoring of civil structures as well as aircraft structures. Nondestructive evaluation of the health of engineering structures is the critical need for the deterioration of infrastructure elements. Structural health monitoring is an essential management tool for safely working of advanced structures. Advanced composite and concrete structures are now being widely used in modern vehicles, ships, civil infrastructures and aerospace industry. In those structures, *in situ* structural monitors are highly desirable to detect a decrease in performance or imminent failure due to the variation of relevant physical parameters such as strain, temperature, corrosion, vibration etc. A typical health monitoring system is composed of a network of sensors that measure the parameters relevant to the state of the structure and its environment. Optical fiber sensors will be ideally suited for the long term continuous structural health monitoring systems. These sensors can be developed to selectively detect the variation of physical parameters. In advanced structures, the location and extent of strain are the important information in order to understand their behavior under loading condition. Several different types of fiber optic sensors have been reported for measuring strain in different structures and beams. Fiber Bragg grating sensors have been considered as promising tools for measuring strain in composite structures and beams [1–3]. Distributed fiber sensors based on Brillouin Scattering have been the focus of great attention for measuring strain distribution in large structures [4–6]. However in all these sensors, complexity arises during implementation and also the measurement error increases for large strain difference. Interferometric sensors are very attractive because of their high resolution and sensitivity. Different types of interferometric sensors based on Mach–Zehnder, Michelson, Fabry–Perot, Sagnac etc. have been reported for measuring strain in different structures [7–9]. But in these two beam interferometers, the reference and sensing arms are placed at different locations which can lead to error in measurement. Also the accuracy of measurement depends on the extraction of phase from the interferogram.

In the present work, we develop two-mode fiber interferometer using birefringent fiber for measuring strain in a simply supported beam. Modal interference in optical fibers has been reported by several workers for its application in sensors [10–12]. In interference phenomenon, the determination of phase has been an active area of research, as it carries the key information of the physical parameters. Over the years, different methods have been demonstrated for phase retrieval from interferogram. Phase shifting techniques [13,14], Fourier transform method [15], Synchronous method [16], Quasi one frame algorithm method [17], Regularization technique with low pass filtering [18] were reported to determine phase from the fringe pattern. In recent years, more advanced techniques such as windowed Fourier transform method [19], parameter estimation method [20] and wavelet transform method [21] have been proposed for phase extraction. For higher phase resolution at a high temporal bandwidth, a technique based on sinusoidally modulated phase shifting interferometry has been reported [22]. The above phase retrieval methods may be either

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temporal or spatial. In the temporal techniques, three or more phase steps are required for reducing the errors. In the spatial techniques, a single interference pattern is used, but it requires a large number of fringes in the pattern. All of these techniques require global processing to find the phase at a particular point i.e. full length of data set is utilized for phase determination. For example, in FTM method, by Fourier transform, the point wise information is globally distributed over the whole pattern. In our work, we have used the data dependent system (DDS) method for phase extraction from modal interference pattern. The DDS methodology analyses discrete data to develop a statistically adequate mathematical model for a real system. There is no information loss between the data and the model, if the model is adequate. The method utilizes the correlation between the neighbouring data points of a profile. The model takes into account the dynamic dependence between the neighbouring data points that represent a real system. The dynamic dependence is expressed by a regression model [23]. The method has been widely used in manufacturing and process design [24].The method has also been used for phase extraction from noisy interferogram [25]. In our earlier work, we have used DDS method for extraction of phase in a Mach–Zehnder type fiber interferometer [26]. In the present context, we extract phase from the beat signals produced due to the interference of LP_{01} & LP_{11}, LP_{01} & LP_{02} and LP_{06} &LP_{07} modes in single mode birefringent fiber and multimode fiber under loading conditions in a beam. Higher order modes have more coupling coefficients than lower ones [11]. A set of data has been selected from the interferogram and characterized by means of autoregressive (AR) model. The autoregressive parameters determine the self coherence function of the pattern and it would provide the phase information due to change in strain. The group delay obtained from the phase contour is utilized to determine the strain of the beam under loading conditions.

2. Modal interference

Intermodal interference within a single mode fiber is based on the principle of modal Mach–Zehnder interferometer. In single mode fiber, although fundamental mode is guided, higher order modes can be propagated for wavelength above the cut off. In a single mode fiber, if the '*V*' parameter is set in the range 2.408–3.8317, then LP_{01} & LP_{11} modes are excited and in the range 3.8317–5.1356, LP_{01} & LP_{02} modes are excited with the launching of axially symmetric light beam at the input end. The fundamental mode LP_{01} is two fold degenerate and LP_{11} mode is four fold degenerate with *x* or *y* polarizations. The modes that can propagate within a two-mode fiber are $LP^x_{01}, LP^y_{01}, LP^{e,x}_{11}, LP^{e,y}_{11}, LP^{o,x}_{11}$ and $LP^{o,y}_{11}$. In low birefringence fiber, both LP_{01} mode and LP_{11} mode have their same propagation constants in *x* and *y* polarizations. However, in high birefringence fiber, degeneracy is lifted and different polarization modes will have different propagation constants [27]. Similar phenomenon occurs in LP_{02} mode, but in conventional communication fibers, propagation constants are equal in *x* and *y* polarization. In the present analysis, intermodal beating has been considered, e.g. LP^x_{01} and LP^x_{11} or LP^y_{01} and LP^y_{11}. Higher order modes e.g. LP_{06} & LP_{07} are excited by splicing a single mode fiber with a multimode fiber with no axial offset between them.

The intensity pattern due to the interference of two LP modes may be written as

$$I(r,\phi) = A_1^2 f_1^2(r) + A_2^2 f_2^2(r)\cos^2\phi + 2A_1A_2 f_1(r) f_2(r) \times \cos\phi\cos(\Delta\beta L - \Delta\theta), \tag{1}$$

where A_1 and A_2 are the amplitude coefficients of the two LP modes, and f_1 & f_2 are their radial distribution functions. In the third term of Eq. (1), $\cos(\Delta\beta L - \Delta\theta)$ contributes towards the change in phase due to external perturbations, where $\Delta\beta = \beta_1 - \beta_2$, represents the change in propagation constants of LP modes and $\Delta\theta = \theta_1 - \theta_2$. Whenever there is a change in external disturbance, $\cos(\Delta\beta - \Delta\theta)$ will change due to the variation of $\Delta\beta L$, and accordingly intensity pattern will change, otherwise it remains constant. A small perturbation due to strain at one point of the fiber causes a coupling of light to the other mode. The phase delay due to the different mode velocities leads to a beat frequency. The phase difference between the two modes may be written as

$$\Delta\Phi = (\beta_1 - \beta_2)L, \tag{2}$$

where *L* is the distance of light propagation along the fiber.

Under weakly guiding approximation, the propagation constant β_i ($i = 1,2$) can be expressed in terms of normalized propagation constant b_i as

$$\beta_i^2 = k_0^2\left[n_2^2 + b_i(n_1^2 - n_2^2)\right], \tag{3}$$

where k_0, n_1 and n_2 are the free space wave vector, core and cladding refractive index, respectively.

Assuming the fiber as homogeneous material in elasticity, the refractive index variation under strain can be written as [12]:

$$\frac{\partial n_i}{\partial L} = \frac{-n_i^3}{2L}\left[p_{12} - \sigma(p_{11} + p_{12})\right], \tag{4}$$

where p_{11}, p_{12} are Strain Optic Coefficients (for fused silica 0.12 and 0.27, respectively), σ is the Poisson's ratio (0.17).

In our work, we consider a simply supported beam where a concentrated load is applied at the center of the beam. If the fiber is attached at the distance '*Y*' from the neutral axis in the direction of the beam length, then the strain distribution within elastic limit is given by

$$S(Z) = \frac{WY}{4EI} Z, \tag{5}$$

where *E* and *I* are the elastic modulus and the moment of inertia with respect to the neutral axis, *W* is the load applied. As the strain is symmetric with respect to the center of the beam, the Eq. (5) provides the strain distribution for one half of the beam, maximum at the center while zero at the fixed end.

When the strain is applied to the beams, mode coupling occurs and the phase difference between the two modes leads to a change in interferogram pattern. The interferogram is captured by a CCD camera and the intensity distribution in one dimension can be expressed as

$$I(x) = 2I_0(x) + \Gamma(x) + \Gamma^*(x), \tag{6}$$

where $\Gamma(x)$ denotes the self coherence function and $\Gamma^*(x)$ is its conjugate, $I_0(x)$ is the background intensity and *x* is the pixel number. The argument of this coherence function will provide the required phase information due to measurand (i.e. strain, temperature, pressure etc.). When the phase is expanded around a centre optical frequency ω_0, it may be expressed as,

$$\phi(\omega) = L\left[\beta(\omega_0) + \beta_1(\omega_0)(\omega - \omega_0) + \frac{1}{2}\beta_2(\omega_0)(\omega - \omega_0)^2 + \frac{1}{6}\beta_3(\omega_0)(\omega - \omega_0)^3 + \cdots\right] \tag{7}$$

where $\beta_m = \left|\frac{d^m\beta}{d\omega^m}\right|_{\omega=\omega_0}$, $m = 0,1,2,3,\ldots$ represent the imbalances in the propagation constant β and its derivatives. Using DDS method, the phase is recovered from the interferogram and the values of the coefficients of Eq. (7) are determined. They would provide the values of the measurand producing the modulation of group delay.